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基于阿基米德螺旋线的低 *g* 值微惯性开关

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摘要：低 *g* 值惯性开关是一种对线加速度敏感并在施加的加速度作用下完成闭合的惯性装置。由于微小尺寸的限制，低 *g* 值(1－30 *g*)惯性开关只能设计为微质量块和低刚度支撑梁的结构。为了获得低刚度，设计了基于阿基米德螺旋线的平面螺旋梁结构。微开关由一个带触点的基座、一个惯性敏感单元以及框架和封盖组成。惯性敏感单元则由一个居中的质量块和支撑它的螺旋梁组成。在加速度作用下可动的质量块发生位移，与其下的触点接触，实现开关的闭合。惯性敏感单元采用有限元软件 ANSYS 进行分析，采用 UV-LIGA 工艺制作。进行了离心试验以获得低 *g* 值惯性开关的闭合门限。经 3 次测试，闭合门限值分别为 21.22，21.39 和 21.20*g*，平均值为 21.27*g*。测试结果表明，低 *g* 值惯性开关具有 0.5*g* 的闭合精度，多次测试重复性较好。

关　键　词：惯性开关；低 *g* 值开关；阿基米德螺旋线；微机电系统
中图分类号：TM56　　**文献标识码**：A

Low-*g* micro inertial switch based on Archimedes' spiral

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Abstract: The low-*g* inertial switch is a kind of inertial device sensitive to the linear acceleration and achieves the switch closure when subjects to the applied acceleration. Due to its micro size, the switch is designed as a structure with the micro mass and low stiffness. To achieve a low stiffness beam in a micro plane, the planar spiral beam based on Archimedes' spiral is designed. The inertial switch is composed of a substrate, a frame structure, a cover plate and an inertial sensing element containing a sensor mass and a spiral beam. After analysing the inertial sensing element with an ANSYS and fabricating with an UV-LIGA, the laboratory centrifuge tests are performed on the low-*g* inertial switch to measure the on-state threshold. The result of the test is 21.27*g*, which is the average of 21.22, 21.39, and 21.20*g*. It is shown that the low-*g* mechanical inertial switch has a closed precision of 0.5*g* and good repeatability in multiple tests.

Key words: inertial switch; low-*g* switch; Archimedes' spiral; MEMS

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1 Introduction

The low-g inertial switch is a kind of inertial device for sensing linear acceleration and achieving switch closure when subjects to the applied acceleration[1], which is different from the one in shock or impact applications[2-3]. Low-g generally means linear acceleration range from $1g$ to $30g$ ($1g=9.8\ \mathrm{m/s^2}$). Due to micro size limitation, the low-g inertial switch should be designed a structure with the micro mass and low-stiffness beam. As far as we know, it is hard to achieve low stiffness using straight beam in a micro plane[4-5]. Moreover, traditional helical springs can achieve low stiffness easily but can only be made in macro sizes and can not be fabricated with the MEMS. To achieve the micro low-stiffness beam, a planar spiral beam based on Archimedes' spiral is designed. The spiral beam can be made with a very long beam in the limited plane without difficult process.

2 Structure and principle

A schematic view of the switch is illustrated in Fig. 1.

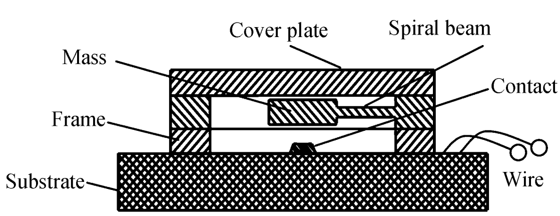


Fig. 1 Schematic view of the switch

The micro switch consists of a substrate with a contact tip on it, a frame, an inertial sensing element and a cover plate. The inertial sensing element consists of a mass in center supported by a spiral beam. The movable mass is displaced to the contact when it subjects to acceleration. The switch is closed when the two parts contact.

3 Design

Archimedes' spiral is a kind of spiral as the polar equation (1) described:

$$r=\rho\theta\ , \tag{1}$$

where, r is the polar radius, and ρ is a constant, θ is the angle of rotation which unit is rad. The distance between two arms in the spiral is $2\pi\rho$.

The inertial sensing element is the main structure of the switch. Calculation and analysis is performed on the element to achieve the displacement of the Z direction when it subjects to acceleration[6].

To avoid cross coupling in the dynamic closure of the switch, width of the spiral beam must be designed large enough and the thickness of the spiral beam must be designed small enough. Thus the main deflection can occur in the Z direction. The prescribed ON-state threshold of the switch is $20g$. If the Z directional maximum displacement of the movable part under $20g$ acceleration is equivalent to or greater than the distance between the two contacts, then the switch could be closed.

3.1 Calculation

For simplified representation of the model, the abbreviated equation (2) is given only considering torsion:

$$z=\frac{\rho^3}{\boldsymbol{GI}_p}\int F(\theta)\theta^2\sqrt{1+\theta^2}\,\mathrm{d}\theta\ , \tag{2}$$

where, $\boldsymbol{G}$ is the shear modulus, $\boldsymbol{I}_p$ is the polar moment of inertia, $F(\theta)$ is the inertial force applied to the element, which is illustrated in equation (3):

$$F(\theta)=[m_1(\theta)+m_2]\boldsymbol{a}_z\ , \tag{3}$$

where, $\boldsymbol{a}_z$ is the acceleration in Z direction applied to the element, m_2 is the mass of central mass, $m_1(\theta)$ is the distributed mass of spiral beam assassociated with θ, which is denoted in equation (4):

$$m_1(\theta)=Dbh\rho\int\sqrt{1+\theta^2}\,\mathrm{d}\theta\ , \tag{4}$$

where, D is the density of material, b and h are the width and thickness of the spiral beam, respectively.

The relationship between the displacement in the Z direction and the angle of rotation (Z-θ) according to equation (2) is plotted, as shown in Fig. 2.

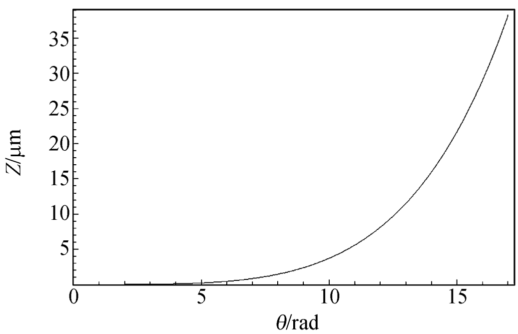


Fig. 2 Diagram of displacement of Z direction with angle of rotation θ

From the diagram we know that the displacement of the Z direction increases nonlinearly with the angle of rotation θ. But the displacement of the Z direction varies with acceleration linearly. The maximum displacement of the Z direction is 38.2 μm according to the calculation.

3.2 FEM Analysis

The inertial sensing element is analysed with ANSYS, the finite element software. The applied boundary condition is that the square-periphery is fixed and the load gravity is $20g$. The analysis result is illustrated in Fig. 3.

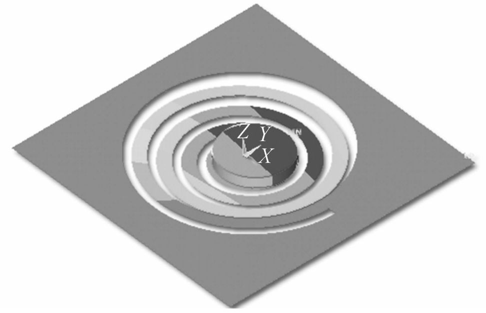
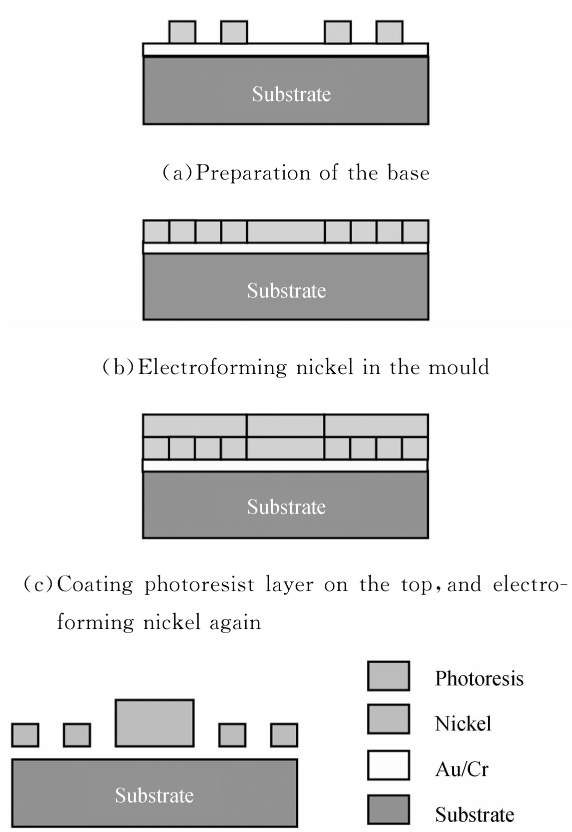


Fig. 3 Analysis of inertial sensing element (size is 5 mm×5 mm×15 μm, central mass size is Φ1.5 mm×0.2 mm)

From the picture we find that the maximal deflection occurs on the edge of the mass, which is shown as the deep grey part. It shows that contact will not occur on all the surface of the mass when the inertial switch remains closed. This kind of contact mode will avoid sticking contact caused by the electrostatic force[7]. The maximal deflection of the inertial sensing element using FEM analysis is 37.8 μm, which is consistent with the calculation result.

4 Fabrication

The inertial sensing element is fabricated with UV-LIGA process, its main fabrication steps are shown in Fig. 4.



(a) Preparation of the base

(b) Electroforming nickel in the mould

(c) Coating photoresist layer on the top, and electroforming nickel again

(d) Dissolving seed layer and photoresist and releasing nickel layer

Fig. 4 Main fabrication steps of inertial sensing element

Firstly, a metal seed layer (Au/Cr) about 1 μm thickness is sputtered on the insulated substrate. Then photoresist is coated and patterned into the spiral and mass mould, which is shown in Fig, 4(a).

Secondly, nickel about 15 μm thickness is electroformed in the mould, which is shown in Fig. 4(b).

Thirdly, a photoresist layer is coated on the previous layer and patterned into the mass mould only. Nickel about 200 μm thickness is electroformed in the mould, which is shown in Fig. 4 (c).

Finally, the nickel layer is all released after the seed layer and the photoresist is dissolved, which is shown in Fig. 4(d).

The inertial sensing element as well as other parts are assembled into a switch, which is shown in Fig. 5.

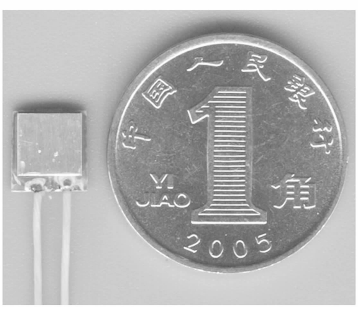


Fig. 5 Picture of the switch compared with a coin (chip size is 5 mm×5 mm×0.5 mm)

5 Tests

Laboratory centrifuge tests are performed on the low-g inertial switch to measure the on-state threshold. An oscillograph is used to monitor the closure process, the test method is shown in Fig. 6.

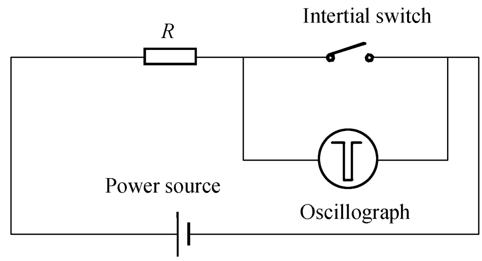


Fig. 6 Schematic diagram of test method

Tests and measurements are performed three times. The waveform and threshold of the on-state are shown in Fig. 7 and Tab. 1, respectively.

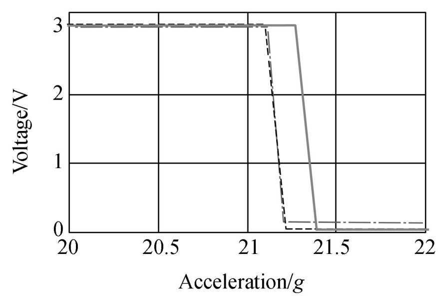


Fig. 7 Waveform of ON-state in centrifuge test

The ON-state threshold of the switch is 21.27g for the average of 21.22, 21.39, and 21.20g, which shows that the low-g inertial switch is closed with high precision and the repeatability is good in multiple tests.

Tab. 1 ON-state threshold by centrifuge test

	First test	Second test	Third test
Acceleration	21.22g	21.39g	21.20g
Average		21.27g	

6 Conclusions

The low-g micro inertial switch based on Archimedes′ spiral is designed and fabricated. Tests are performed to verify the difference between the test value and the prescribed value. Test results indicate that the test value 21.27g is greater than the prescribed value 20g. The fabrication and stresses in the structure may cause 6.35% error. Next work is to improve accuracy in fabrication and to reduce stresses of electroformed structures.

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